A STUDY OF BIOGAS UTILIZATION EFFICIENCY HIGHLIGHTING INTERNAL COMBUSTION ELECTRICAL GENERATOR UNITS

Undergraduate Honors Thesis

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ABSTRACT

The purpose of the study was to determine the efficiency of methane utilization for a currently operating anaerobic digestion system on an agricultural facility. A dairy anaerobic digester was chosen for the study. A cogeneration system was implemented at this location using three biogas gen-set's, each with a 710 kW capacity. Methane flow and pressure data, and electrical output (kW) data were collected on three units operating at the facility from January 23, 2009 to February 2, 2009. A sample was taken every minute. Hourly averages were then calculated and analyzed. An energy balance was then used to calculate instantaneous efficiency.

Instantaneous gen-set efficiency over this period was found to be 25.51% with a 5.93% standard deviation. This value was higher than that found in previous studies, of 22% electrical power to methane power. Lower methane energy flow rates were found to have a positive effect on gen-set efficiency; however total output was small compared to the generator size. Efficiency stabilized from 1358 kW (29% efficient) to 1958 kW (22% efficent) methane flows. Gen-set efficiency had a similar trend when compared to biogas flow rate, with higher efficiency at lower flow rates and lower efficiency at higher flow rates. Efficiency stablized when biogas flow was 117 cubic feet per minute to 148 cubic feet per minute. Methane content in the biogas was assumed 55.5% by volume from previous tests.

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INTRODUCTION

As animal agricultural operations become increasingly consolidated, waste management becomes a greater issue. One strategy to reduce, disinfect, and better utilize animal waste is to run it through an anaerobic digester and from it harvest biogas, containing mostly methane. The biogas collected is flammable and this provides several options for utilization. Some common uses include flaring, heating (home, water, etc) and internal combustion (creating rotational power). In many cases, internal combustion engines are attached to electrical generators which produce electricity for on farm use or sale to an electric company.

In light of economic return on the installment and operation of anaerobic digesters, efficiency is a major aspect. Additionally, increased energy demand worldwide and rural development stress greater efficiency. Therefore, efficient biogas utilization is key to an anaerobic digester's economic return and practicality. The question is what efficiency does biogas utilization systems actually attain? The purpose of this study was to determine the efficiency of methane utilization for a currently operating anaerobic digestion system on an agricultural facility.

LITERATURE REVIEW

The discovery of biogas can be first traced back to the 17th century when Van Helmot noticed flickering lights beneath the surface of swamps and connected it to a flammable gas produced by decaying organic matter. In the scientific world, Volta noted as early as 1776 that biogas production is a function of the amount of decaying plant material and that the biogas is flammable under certain conditions (Marchaim, 1992).

The chemical composition of methane was established by Henry and Davy Dalton in 1810 via methane from coal mines. This was soon linked to the biogas involved in

Volta's scientific discussion. By 1884, a student of Pasteur in France, Gayon, had anaerobically produced biogas by suspending cattle manure in a water solution at 35 Celsius. At that time he was able to obtain 100 liters of biogas per meter cubed of manure (Marchaim, 1992).

Anaerobic digestion has been studied thoroughly. The discovery and separation of certain kinds of bacteria involved in the digestion process were begun as early as 1906 by Sohngen. By the 1920's Buswell was able to track and record the movement and uses of nutrients such as nitrogen through the digestion process. Barker in the mid 20th century was able to isolate and perform biochemical studies on a large number of the bacteria involved in anaerobic digestion.

Today there is a desire for development of large scale bio digesters in numerous applications. Four main reasons why bio digestion is being pursued currently are (Marchaim, 1992):

1. Improvement of sanitation for treatment of high organic solid, high nutrient, and high biological wastes and waste waters
2. Reduction in unpleasant aroma associated with animal waste
3. Production of energy
4. Production of high quality fertilizers

Anaerobic digestion is the degradation of organic materials by micro organisms able to utilize molecules other than oxygen as hydrogen acceptors. More simplistically, the bacteria must be in an environment without oxygen (Price & Cheremisinoff, 1981). The process of anaerobic digestion on a molecular level involves many different kinds of bacteria. The process in general however can be summed up in Figure 1 below (Price & Cheremisinoff, 1981).

$$Organic\ Matter \xrightarrow{anaerobic\ microorganisms} CH_4 + CO_2 + H_2 + N_2 + H_2S$$

Figure 1: Anaerboic Molecuar Process (Price & Cheremisinoff, 1981)

The complex organics on the left of Figure 2 are organic wastes introduced as the feedstock of the digester, such as dairy cattle manure. In the hydrolysis and fermentation stage, bacteria break down the long chain organics into higher organic acids, hydrogen, and acetic acid. In stage 2, the higher organic acids are further broken down into hydrogen and acetic acid. In the final stage, methanogensis, bacteria utilize the hydrogen and acetic acid to form methane, $CH_{4.}$ The bacteria involved in the digestion process have many constraints for effective operation including temperature, pH and acidity, moisture, and substrate nutrients. (Price & Cheremisinoff, 1981).

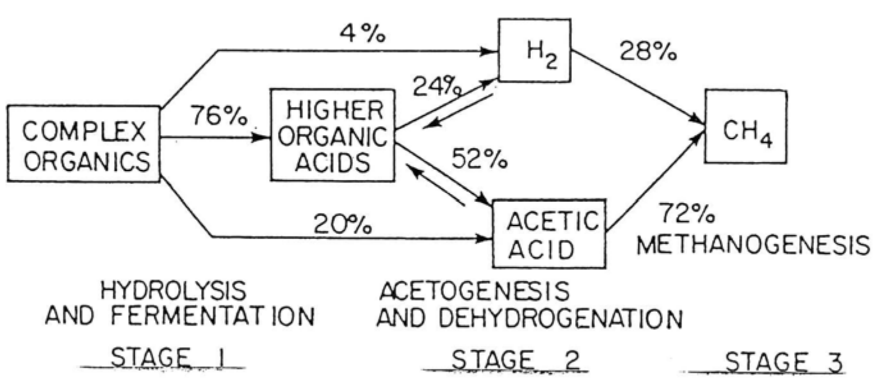

Figure 2: Anaerobic Digestion Stages (Marchaim, 1992)

Though there are many factors that affect the rate of biogas production in anaerobic digesters, one of the most influential is operating temperature. Digestion can occur in a temperature range from 4 to 60 degrees Celsius. However, certain temperature ranges provide specific advantages. There are two temperature ranges that provide the best advantages in anaerobic digestion: mesophilic and thermophilic (Constant & Naveau, 1989). The mesophilic range (30-40 degrees Celsius) is known for providing a more stable gas production, as the micro organisms that thrive in that range are less upset by temperature fluctuations, which is a constant issue in digesters management (Constant & Naveau, 1989). Also, the mesophilic range is fairly close to room temperature, which leads to less energy input for temperature stability in the digester feedstock. The thermophilic temperature ranges (45-55 degrees Celsius) has several advantages over mesophilic, including shorter solid retention time, increased digestion efficiency, better sludge dewatering characteristics, and increased destruction of pathogenic organisms (Constant & Naveau, 1989). To make digesters economical to install and operate, fast digestion times and easy waste processing characteristics make thermophilic operation desirable. The most encouraging advantage to thermophilic operation is that the gas production rate is twice that of mesophilic operation, which leads to lower digester volumes, and consequently lower initial cost (Price & Cheremisinoff, 1981). There are several disadvantages to thermophilic operation. The first is that maintaining a constant temperature well above room temperature is more difficult and requires greater management and energy inputs. Secondly, methanogenic bacteria that thrive in the thermophilic region tend to be easily upset by temperature fluctuation (Price & Cheremisinoff, 1981). In fact, one study from Marchaim shows that the acceptable temperature variation for stable gas production in the mesophilic range is approximately ±2.8 degrees Celsius. In thermophilic operation the acceptable temperature variation was found to be only ±0.8 degrees Celsius (Marchaim, 1992).

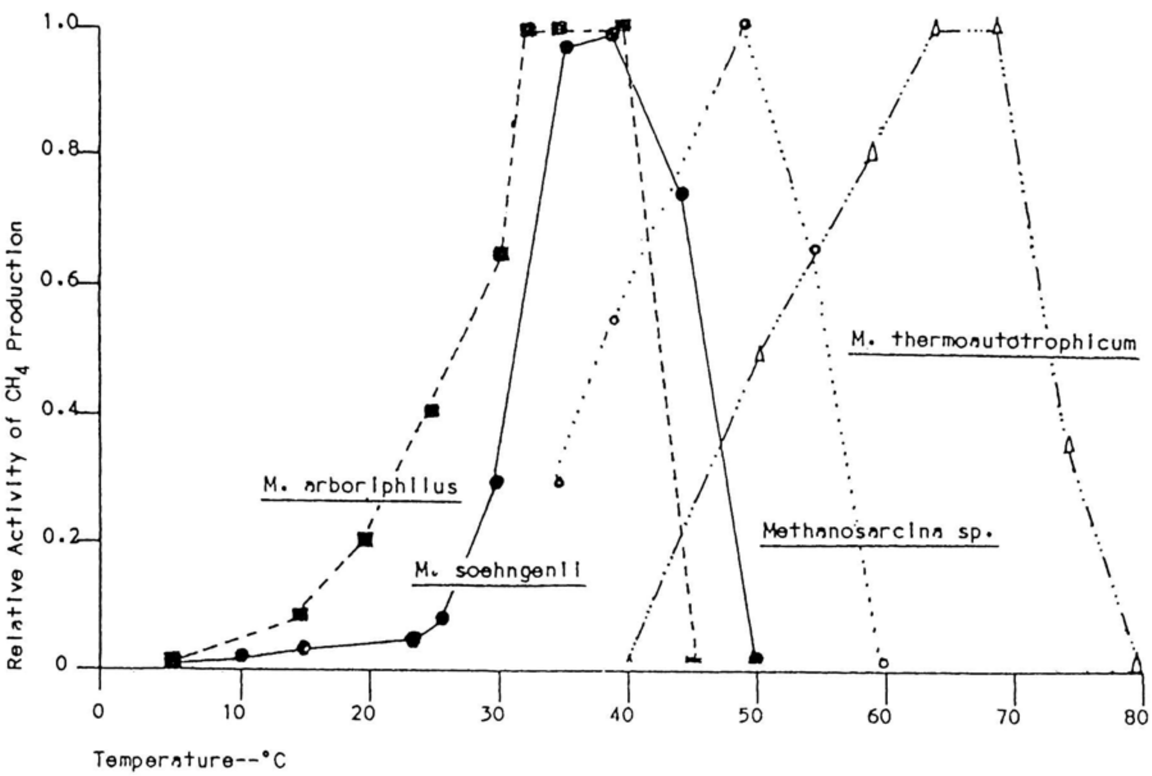

Figure 3: Methane Production of Bacteria in the Mesophillic and Thermophillic Ranges (Marchaim, 1992)

The limitations of biogas utilization are caused by the composition of the biogas. The average methane quantity of biogas is around 60% (Price & Cheremisinoff, 1981). Even though biogas does contain other components, the only other major component is carbon dioxide.

Table 1: Methane Content of Biogas by Source (Constant & Naveau, 1989)

	A : From biogas plants			B : From landfills
Molecular species	Wheatley (1979)	Fox (1984)	Hobson et al. (1981)	Meynell (1983)
Methane, CH_4	52-95 (a)	60-70	60-70	45-65
Carbon dioxide, CO_2	9-40	30-40	30-40	34-45
Hydrogen sulphide, H_2S	0.001-5.7	0.05-2	0.007-0.2	0.5-100 10-5
Dihydrogen, H_2	0.01-1.2		2	0-1
Dinitrogen, N_2	0.1-18	1	4	0-1
Dioxygen, O_2	0.02-6.5			0-1
Argon, A	0.001			
Carbon monoxide, CO	0.001-2.1		0.001-1	
Ammonia, NH_3	traces			traces
Organics	-			5 10-5

(a) All figures are % by vol.

Methane is the useful component of the biogas as it can be used as a fuel. Despite its high level of methane, biogas does have some inherent problems. First, the critical point of biogas is very low. The critical point of a gaseous substance is the thermodynamic state at which the liquid and gas phases of a substance coexist in equilibrium (Price & Cheremisinoff, 1981). For example, propane has an ideal critical point that allows for storage in the liquid phase, creating smaller storage containers and easier gas handling. The critical point of methane is -82.5 degrees Celsius and 46.7 bar. This means that biogas cannot be liquefied at a temperature above -82.5 degrees Celsius, which is a major limitation in biogas utilization (Constant & Naveau, 1989).

Table 2a: Critical Point of Various Gases (Constant & Naveau, 1989)

	H_2	N_2	NH_3	O_2	CH_4	CO_2	H_2S	C_3H_8	C_4H_{10}
Temperature (C°)	-239.9	-147.1	132.4	-118.57	-82.5	31	100.4	96.6	152
Pressure (bar)	13.1	34.2	113.9	50.8	46.7	73.85	90.1	42.5	37.9

(According to Weast and Astle, 1980)

Table 2b: Energy Content of Various Gases (Constant & Naveau, 1989)

Combustible	MJ kg^{-1}	MJ m^{-3}
Methane	50.0	35.9
Purified biogas (90%)	45.0	32.3
Mean biogas (60%)	30.0	21.5
Butane	45.7	118.5
Propane	46.4	90.9
Methanol	19.9	15.9 10^3
Ethanol	26.9	21.4 10^3
Gasoline	45.0	33.3 10^3
Diesel	42.1	34.5 10^3

*At 1 atm and 0°C

Another problem with biogas is that it contains three undesirable components – carbon dioxide, water, and hydrogen sulfide. The problem with the high amounts of carbon dioxide is dilution of methane. If the biogas is to be stored, a large amount of space would be wasted on storing carbon dioxide. Similarly, if it was to be piped to another location, energy would be wasted in pumping the carbon dioxide. In some cases, compression of carbon dioxide can lead to the creation of carbonic acid which can deteriorate metering mechanisms and storage components (Wise, 1983). Biogas also contains water, which has several detrimental effects. First, the water tends to condense in a compressed state, therefore taking up space in the storage containers. Most importantly, the water reacts with the hydrogen sulfide in the biogas, and creates a very corrosive acid. When burned, the chemical reaction leads to the creation of sulfur dioxide, which is also very corrosive and can lead to acid rain (Wise, 1983).

In some cases, purification of the biogas is not required, depending on its composition, level of hydrogen sulfide, and utilization. However, for use in direct home heating, transportation, and internal combustion engines, purification may be required (Hobson, Bouslield, & Simmers, 1981). The use of scrubbers in a digestion system should only be used when necessary as they add cost, management, and complexity to the system.

Methane utilization is an important piece of a bio digesters economic viability. Not only must the system be efficient in time, cost, and management, it must be able to withstand the problems that occur with biogas production. Biogas tends to be a non-constant flow, especially on a small scale, resulting in the system requiring storage devices, and flow and pressure regulators. Essentially there are two basic ways to utilize biogas methane – (1) open flame heat and (2) internal combustion.

For open flame heat there are several easy applications. One option that has been exercised is flaring. Flaring simply is burning the biogas into the atmosphere without any intention for heat generation. Even though this seems counter intuitive, it does have some benefits. First, flaring safely disposes of methane preventing any unsafe situation, as methane is a deadly odorless gas. Also, by burning methane, CO_2 and water are created. The current potential global warming situation has led to support for burning methane as it is about 21 times more powerful as a green house gas than CO_2, by weight (EPA, 2006). In the United States, a system of carbon credits is being created, that could also create cash flow for just flaring due to the environmental implications stated above (EPA, 2006).

Another application of open flame methane utilization is heating. In many cases, a dairy or animal operation can heat parlors, nurseries, and offices with methane. Due to the potential of high carbon dioxide and hydrogen sulfide levels, the gas should not be directly burned in a closed area (Hobson, Bouslield, & Simmers, 1981). With the heating costs of many colder climate operations, the bio digester could have a decent return on investment. However, when biogas production is large or in the summer time, not all of the biogas can be used. Therefore another use for the biogas must be implemented. Another problem with using biogas for heat is that in many heat exchanger and gas monitoring systems, vital components are susceptible to corrosion by the hydrogen sulfide in the gas. This could increase maintenance cost, or cause failure of the system (Price & Cheremisinoff, 1981).

Another potential problem of open flame burning is the flame velocity of methane. As can be seen in the table below, many commonly used combustible gases burn significantly faster than methane.

Table 3: Flame Velocity of Various Gases (Constant & Naveau, 1989)

Combustible	Flame velocity (v, cm s^{-1})
Methane (CH_4)	43.4
Hydrogen sulfide (H_2S)	39.1
Propane (C_3H_8)	45.6
Butane (C_4H_{10})	44.8
Dihydrogen (H_2)	170
Ethanol (C_2H_5OH)	48.4
Methanol (CH_3OH)	48
Gazoline	40

If the gas nozzle is incorrectly designed, the flame could 'blow out' and create a dangerous situation where unburned gas escapes. Some studies have been done to find the appropriate sizing for holes in a methane burner (Constant & Naveau, 1989). Generally, a natural gas burner nozzle can adapted to burn methane by increasing the orifice size of the nozzle and decreasing the pressure at which the gas is delivered to the nozzle.

The use of biogas in internal combustion engines is another viable option. There are two basic types of engines which can be run with biogas: Spark Ignition (SI, Otto) and Compression Ignition (CI, Diesel) (Marchaim, 1992). The SI engine ignites fuel with a spark plug and generally uses volatile fuels such as light petrol's. In theory, the SI engine should be more efficient than the CI engine. Due to the fact that compression ratio inhibits SI engine efficiency, a CI engine is actually more efficient in practice (Constant & Naveau, 1989). CI engines ignite fuel using compression. At a correct combination of pressure and temperature, fuels will auto-ignite. Therefore, the engine must be designed for the intended fuel, as to hit the correct temperature and pressure (Constant & Naveau, 1989). The stoechiometric air-fuel ratio found in previous studies was 5.71 m^3 air per m^3 of gas for 60% methane biogas (Constant & Naveau, 1989). This ratio should be satisfied for complete combustion of biogas. A table comparing SI and CI engines is shown below.

Table 4: Comparison of Spark Ignition and Compression Ignition Systems (Constant & Naveau, 1989)

Type of engine	SI	CI
Combustible	High octane rating	High cetane rating
Compression ratio	7.5-10.5	15 - 20
Cycle	Isochore	Isobare or mixed
Air-filling coefficient (τ_r)	0.85 - 0.92	0.90 - 0.95
Air-excess (λ)	1 ... 1.2	1.6 ... 2
Effective efficiency (η_e)	0.27 - 0.33	0.33 - 0.38
Specific fuel consumption (g kWh^{-1})	280	240
Effective mean pressure (bar)	10.5	7.5
Max. rotation speed (rpm)	3000 - 8000	500 - 2000
Engine cost	Cheap	Expensive
Life span	Short	Long
Usual application	Intermittent	Intensive

(From Martin, 1980, by courtesy of the author). The air-filling, τ_r, is the mass of input air divided by the density of air at the temperature and pressure of reference, and by the volume of the cylinder.

There are three main engine types on the market today. The first is pure gas SI engine. Most gasoline SI engines in use today can actually be easily switched to run on compressed natural gas, propane, and methane (Emcon Associates , 1980). There are two changes that must be made to ensure proper operation when switching from gasoline to biogas. First, a gas carburetor must be installed, which can be purchased from any company that sells propane burning equipment, and then modified as noted above to make up for the slow flame velocity and increase air consumption of methane burning (Constant & Naveau, 1989). The set up of a general gas carburetor can be seen below.

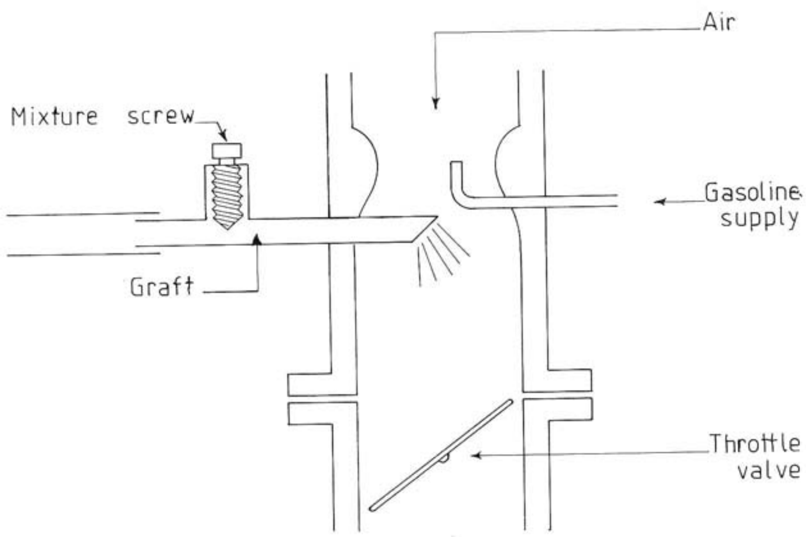

Figure 4: Biogas Carburetor Schematic (Constant & Naveau, 1989)

Secondly, spark plugs with high temperatures must be installed to counter the high combustion temperature of methane (Constant & Naveau, 1989).

A second type of engine that can utilize biogas is the dual fuel modified CI engine. Due to the slow flame velocity of methane, low speed CI engines are more conducive to bio gas utilization (Constant & Naveau, 1989). These systems are designed to burn diesel fuel while burning biogas. This gives flexibility as to the source of the fuel and increases the efficiency of biogas burning. However, this system requires that diesel fuel to be added regularly which increase maintenance.

The last type of engine that can be used with biogas is the pure gas modified compression engine. A diesel engine is modified and runs only on biogas. The major modifications to the diesel engine include: removal of the injectors, addition of spark plugs, addition of a gas carburetor, and decreasing of the compression ratio (Constant & Naveau, 1989). Even though this is the most complicated way to make a biogas engine, it is the most suitable for biogas. The pure biogas system is more efficient due to its lower speed, higher compression ratio, and sturdier design (Constant & Naveau, 1989).

In any case where constant mechanical power can be utilized, an internal combustion could be a good option. In many cases, the engines are stationary and can run at a constant rate. This situation is ideal, as a generator system can easily be attached. One major advantage of an internal combustion-generator set (gen-set) is that it produces electricity at a constant level. Electricity is more easily used for different functions on an animal operation and can be sold to the local electric utility. There are some technical changes that must be made to the power grid, depending on the situation, to accommodate electricity feeding back into the grid.

Figure 5 shows historical efficiency of gen-set systems. In this particular figure, it represents a unit with co-generation, which implements heat exchangers to capture unused heat from the gen-set. The usable current is about 22% of the energy input, and mechanical energy to the generator about 25%. With cogeneration, 58% of the input energy is used for heating, which increases the overall efficiency to 80% which is much more desirable than the 22% from electricity alone. Cogeneration has been applied to many digesters already due to its significant advantage in energy efficiency (Wise, 1983).

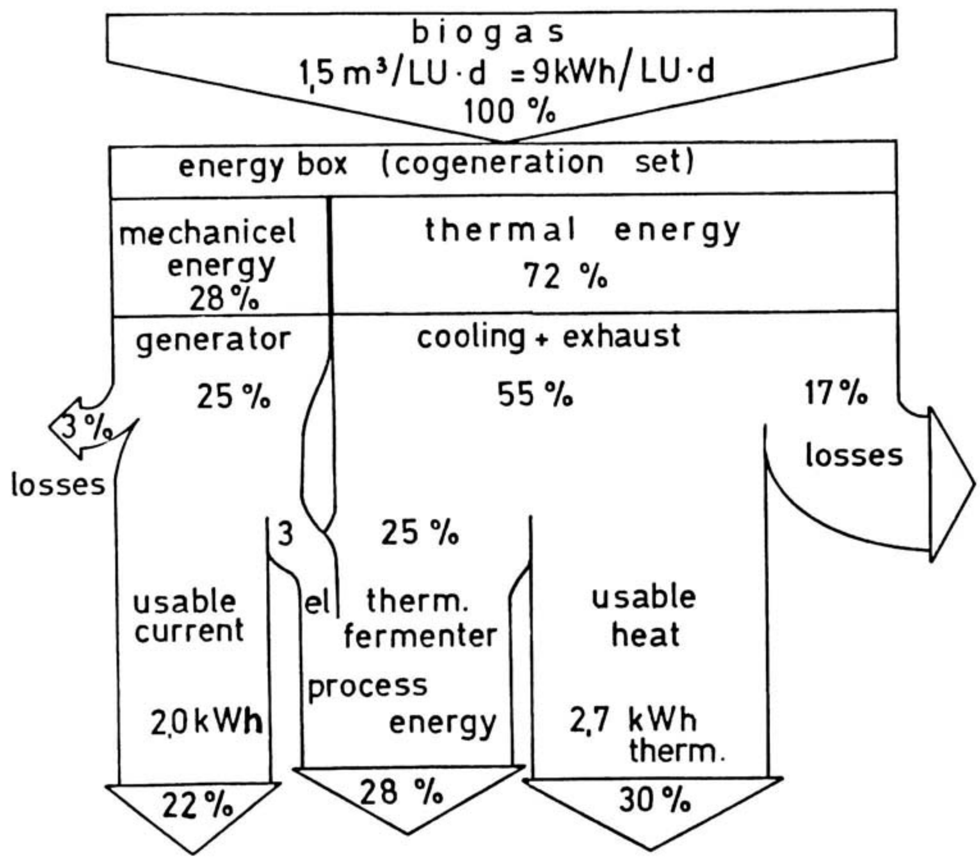

Figure 5: Energy Flow Chart of a Gen-Set Cogeneration System (Wise, 1983)

MATERIALS AND METHODS

The research involved data collection from a gen-set cogeneration unit at Riverview Farm in Minnesota. The biogas was from an anaerobic digestor operating the facility using dairy manure. The data was collected and received by a system already implemented by Martin Machinery, of Missouri. Three gen-sets, each with a 710 kW capacity, were used at this location. The following is a system snap shot, showing the digestor, three gen-sets, pressure regulators, flow meters, and a flare. As can be seen in the figure below, there is also a heat recovery system for each gen-set that utilizes excess or waste heat. Even though this information was of interest to the study, no data could be collected as a volumetric flow meter was not installed on any of the heat exchanger units. Installing one was not within the scope of this study.

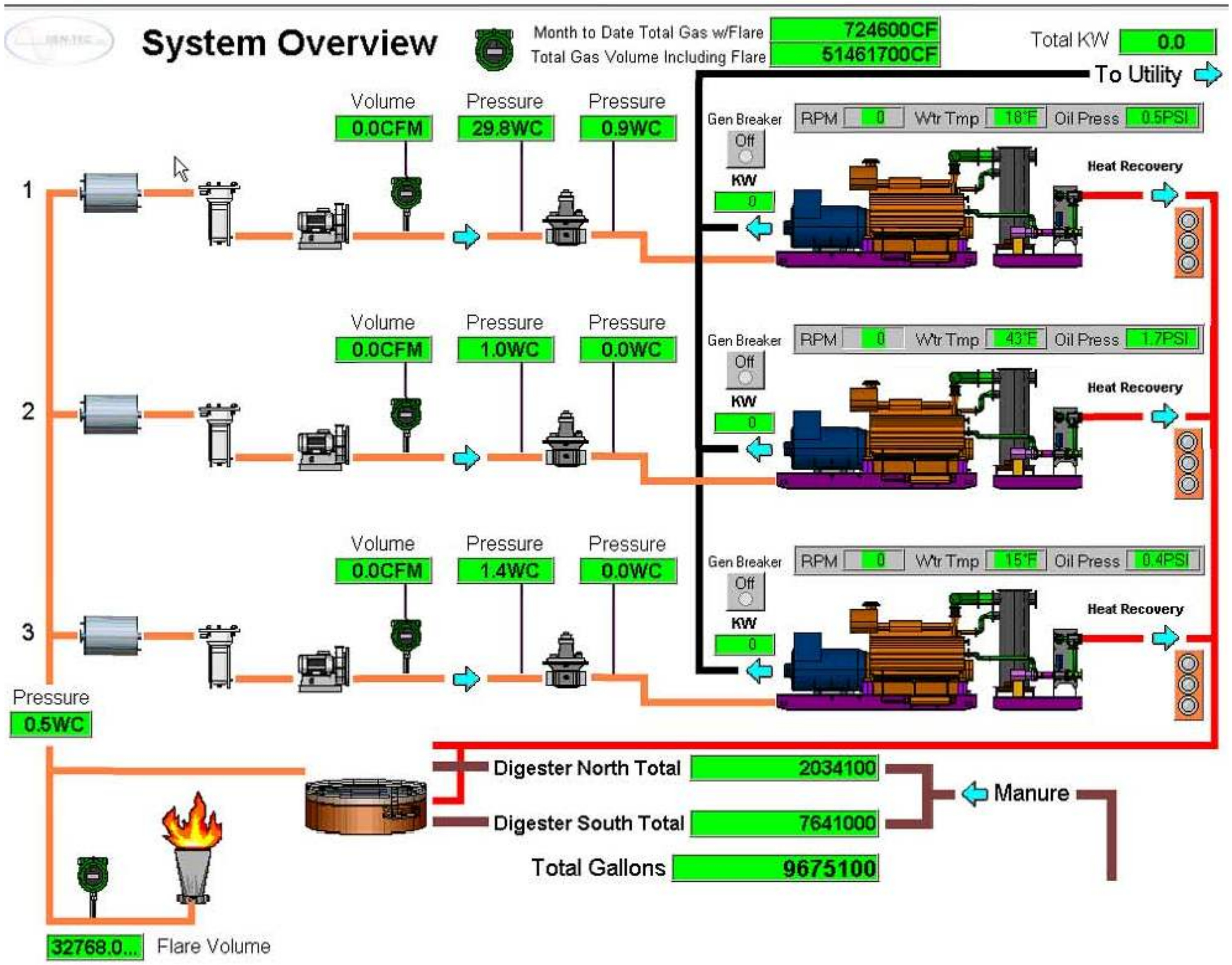

Figure 6: Riverview Farms Digester System Layout

The original farm of interest was a dairy operation in northwest Ohio, called Bridgewater Dairy. Even though the digester and biogas gen-sets were operational at this time, many measurement devices were not in place. Without established measuring devices, complexity and cost of the project increased dramatically. This made Bridgewater Dairy impractical as a source of study, resulting in the change of operations.

The data collection system installed by Martin Machinery takes readings every minute. The data used in this study was from January 23, 2009 to February 4, 2009. The data was further refined to an hourly reading which enabled easy use in Excel, as the minute by minute data consistently outsized Excel's capabilities.

The specific pieces of data used in this study were as follows: day, hour, biogas flowrate, biogas pressure pre-regulator, biogas pressure post regulator, and gen-set output. An overall energy balance was used to analyze system efficiency (Moran & Shapiro, 2008). From previous composition tests at the Riverview Farm digester, the biogas ranged in methane content from 53 to 58% by volume. An average of 55.5% was used in calculations. The Ideal Gas Law was used to find the specific volume at the respective temperature and pressure. Input temperature of the biogas was assumed to be around 110 degrees fahrenheit, as this is in the range of both mesophillic and thermophillic operation, and similar to the temperature of the air coming into the engine from the atmosphere after heating from the unit. The mass flow rate of methane was then found, and from that the energy flow rate was found. The methane flow rate was then compared to the gen-set electrical power output to find an instantaneous efficiency. Excel was used to find the averages and standard deviations.

RESULTS AND DISCUSSION

The averages and standard deviations for pertinent data are summarized below in Table 5 for the time frame studied at Riverview Farm. The biogas flow was very consistent in this particular time frame, at 130.82 cubic feet per minute, and a low standard of deviation of at 19.29 cubic feet per minute. Electrical power output also was fairly consistent however the variation was greater than that of biogas flow. This is explained by an inconsistency in gen-set efficiency and methane content. The specific volume of the biogas varied greatly as the pressures fluctuated with fuel consumption rates and biogas production. The instantaneous efficiency is of interest, noting an average of greater than 25%. As this is the ratio of electrical output to methane input, the gen-set is more efficient than many studied in the past, as noted previously at 22%.

Table 5: Results from Jan 23, 2009 to February 2, 2009

	Average	**Standard Deviation**
BioGas Flow Rate, (cu. ft/min)	130.82	19.29
Electrical Power Output, (kW)	424.07	71.26
Specific Volume, (cu. ft/lb)	53.77	300.82
Instantaneous Efficiency, (%)	25.51	5.93

Also of interest was the instantaneous efficiency at different operating conditions. One important trend was the effect of methane flow in the biogas on gen-set efficiency. As can be seen in the figure below, operating efficiency tended to be greater as the rate of methane into the system decreased. From 521 kW to 1358 kW of methane, there was a significant decrease in efficiency from around 39% to 30%. However, at 521 kW of methane, the total electrical production was 199 kW, well below the capacity of the gen-set, which makes operation at this level impractical due to rate of return on investment. On the other end of the data, at 3030 kW of methane, the electrical production was 501 kW, which is high, but inefficient at 16%. The optimum range for this unit under its settings at the time of data collection was 1358 kW (29% efficient) to 1958 kW (22% efficient). At lower methane flow rates, high gen-set efficiency can most likely be attributed to a more complete combustion of the methane, due to potentially better stoichiometric air to fuel ratios. Likewise, at a greater methane flow rate, less complete combustion led to lower efficiency.

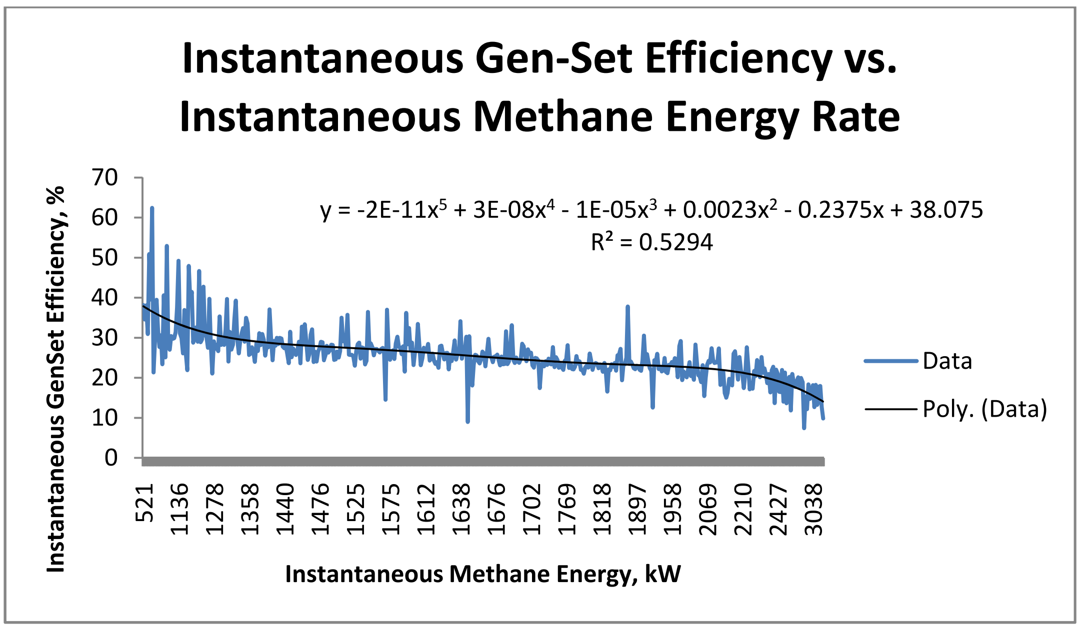

Figure 7: Instantaneous Gen-Set Efficeny vs. Instantaneous Methane Energy Rate

Gen-set efficiency trended similarly with different biogas flows. Even though methane flow and biogas flow are linked, methane flow is also affected by pressure and methane content in the biogas. As can be seen in the figure below, the optimum biogas flow rate for stable electricity production is 117 cubic feet per minute to 148 cubic feet per minute. Even though lower flow rates were more efficient, they did not produce adequate levels of electricity.

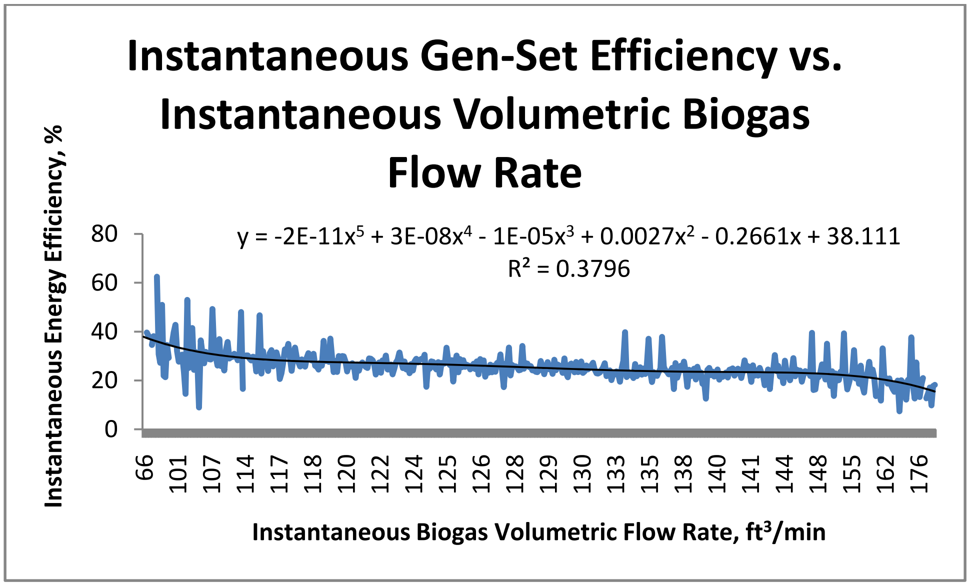

Figure 8: Instantaneous Gen-Set Efficiency vs. Instantaneous Volumetric Biogas Flow Rate

CONCLUSION

The objective of the study was to investigate the energy efficiency of a currently operating gen-set burning biogas from an anaerobic digestor. In gathering biogas and electrical data, a general level of efficiency was found.At the high end of both biogas and methane energy flow, efficiency decreased. For optimal efficiency with correlating acceptable power output, these values should be kept in the range stated in the above section.

This unit was found to be above average in efficiency based upon previous data. This unit, with a cogeneration set up, would be recommended for high methane optimization.

If this study were to be continued, more data should be collected. The cogeneration system should be analyzed to find the total system efficiency. Additionally, a longer window of data should be collected to discern seasonal and managerial effects on biogas output, providing further insight into the versatility of the gen-set. Some conditions may arise during other parts of the year or under different management practices that lead to reduced efficiency. If that were to occur, a different gen-set may be suggested.

Data acquisition systems are also key to further study. When data is collected every minute, half hour or hourly averages should be used to reduce the size and complexity of data handling.

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